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THE PHYSICAL REVIEW

A JOURNAL OF EXPERIMENTAL AND THEORETICAL PHYSICS

CONDUCTED BY

EDWARD L. NICHOLS

ERNEST MERRITT, and FREDERICK BEDELL

LXXIX

OCTOBER 1902.

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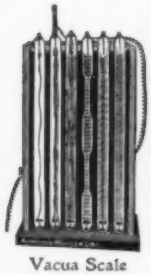

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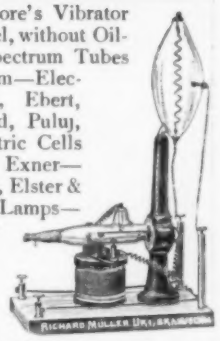

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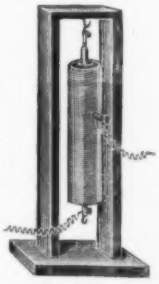

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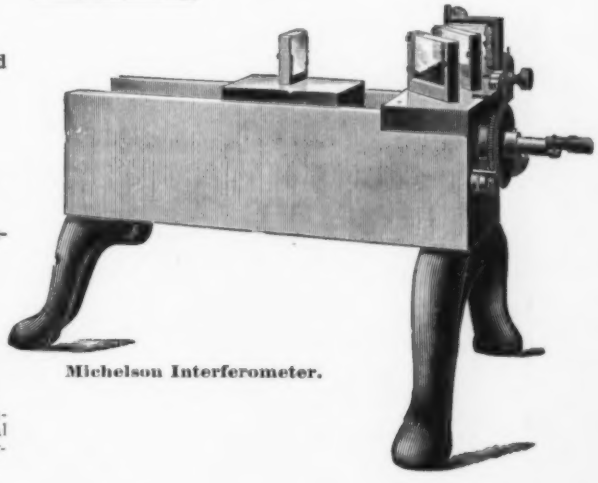

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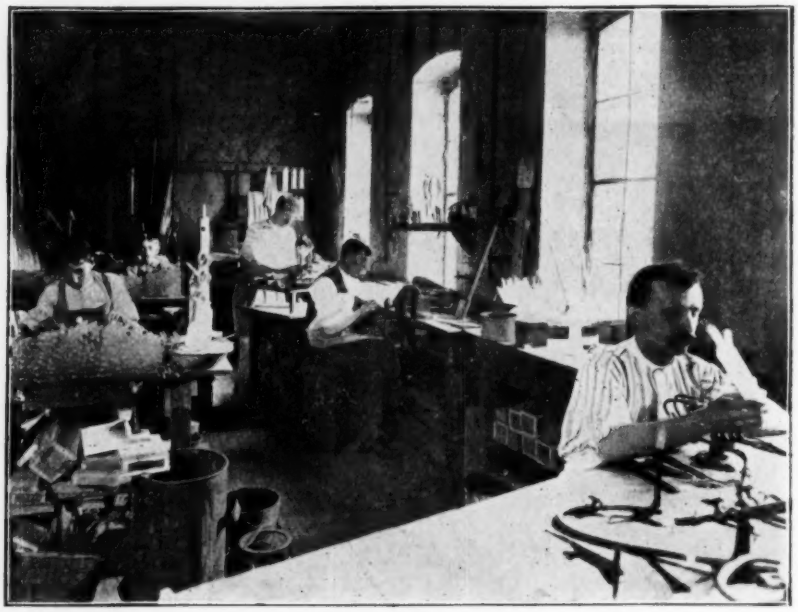

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THE

PHYSICAL REVIEW.

PERSISTENCE OF VISION IN COLOR-BLIND SUBJECTS.

By Frank Allen.

DURING the century which has elapsed since its discovery. color-blindness has been studied from various standpoints, At first it merely aroused curiosity which gradually led to a more careful examination of its peculiarities. In the latter half of the century the importance of the subject was enormously increased by the consideration that in travelling by land and sea human life is often dependent upon the correct perception of color signals by those in charge of trains and vessels. From this economic standpoint the subject has been developed to perhaps as high a degree of excellence as is necessary. But the most interesting aspect of abnormal color vision is that of its relation to the exceedingly involved and complex question of the nature of our perception of light and color.

As is well known color-blindness was first studied by the great chemist, Dalton, who was himself troubled with it. Its investigation subsequently passed to physicists from whom it has been appropriated by the modern school of experimental psychologists and also by physiologists, who have very greatly contributed to our knowledge of the structure of the retina and the functions of its parts, to whom also are due very many of the hypotheses by which the varied phenomena of color vision are correlated.

The study of numerous cases of color-blindness has brought to our knowledge many eccentricities of vision which none of the theories can at present adequately explain. Some of the hypotheses have been devised expressly for the purpose of grouping color-blind subjects into a very few sharply defined classes. While this is a most desirable result to be attained, yet it can only be deprecated that an occasional writer has tried to establish a comprehensive hypothesis upon quite insufficient data. One theory[1] in particular has been founded on but two unique cases of color-blindness described by Holmgren.

The investigation discussed in these pages was undertaken with the object of finding out the nature and magnitude of the variations of abnormal from normal color vision as far as they can be shown by comparing the corresponding measurements of the persistence of vision of the rays of the spectrum.

In a former paper[1] I gave an account of some experiments in which the normal retina was studied under various artificially produced conditions by the Nichols method of the measurement of the duration of visual impressions. Those experiments, it was hoped, would contribute materially towards the solution of the problem of the fundamental color sensations. The present investigation is a continuation of the former both in its object and in the method used, the sole difference being that, instead of the normal retina, the eyes of color-blind persons are studied. As the paper to which reference is made contains a detailed description of the apparatus and of the manner of taking observations employed in both researches, repetition will be unnecessary. In brief, however, the method consists in rotating a sectored disc in front of the slit of a spectrometer at such a speed that there is complete fusion of the intermittent flashes of color of the part of the spectrum under observation. The speed of the disc is electrically recorded on a chronograph which enables the duration of the *greatest* intensity of the light stimulus to be very accurately determined. The time of fusion varies from point to point through the spectrum, but is

[1] Color Sensations, H. R. Droop, Phil. Mag., S. 5, 15, 1883.

[2] Effect on the Persistence of Vision of Exposing the Eye to Light of Various Wave-Lengths, Frank Allen, PHYS. REV., Vol. XI., p. 257, 1900.

dependent, however, only upon the intensity of the light and the sensitiveness of the retina.

The cases of color-blindness examined were all students in Cornell University. Many of them were found by examining several hundred members of one of the classes through the agency of the Military Department of the University. Others were obtained in the physical and chemical laboratories where they betrayed their visual defects in various ways in their work. All subjects were first examined by the Holmgren test and gave unmistakable indications of color-blindness in some degree. In finding the neutral point the Helmholtz color-mixing spectrophotometer[1] was employed. One of the collimator tubes was removed from its ordinary position and remounted so as to permit the light from the slit to be reflected by the prism into the telescope in which it appeared above the spectrum from the other collimator. On looking into the telescope there could be seen only the reflected white light and a narrow band of the spectrum occupying the upper and lower halves of the field respectively. The observer, passing the spectum in review from the red to the violet, set the instrument where the color of the field appeared uniform. The intensity of the white light could be easily varied by rotating the Nicol prism in front of the slit of the collimator. In this way most of the subjects indicated their neutral point with ease and rapidity, though a few were unable to find any at all. In the figures the neutral point is indicated by a short vertical line at the proper wave-length.

The most desired observations were those which determined the persistency curve, the general character of which will be clear on referring to the figures. Including the intervals of rest it generally required about two and a half hours for a person to make the necessary settings of the rotating disc to give sufficiently numerous and reliable data for comparison with the curve obtained by the normal eye. Complete sets of observations were made with both eyes, though in only a very few cases was any difference manifested. Taking the double sets of observations into account, twice as many curves were obtained as are shown in the plates.

[1] Helmholtz, "Physiol. Optik," p. 355.

It will be noticed that the brightest region of the spectrum to the normal eye as indicated by the lowest point of the persistency curve is a little to the green side of the sodium line. As the shifting of this point in the color-blind has been made one of the principal determining factors in their classification by the Hering theory, it will be interesting to observe where it occurs in all the cases. Many of the subjects also determined the position of the brightest point by direct observation which seemed to show that it was shifted rather more than the amount indicated by the position of the lowest part of the persistency curve. The direction of shift was, however, always the same by the two methods, though the magnitude often differed.

In order that the persistency curves may lead to any conclusions concerning the portions of the spectrum to which the retinas of the color-blind are not normally responsive, they are always shown in comparison with a normal curve.

THE NORMAL PERSISTENCY CURVE.

The normal curves which are used as standards of comparison are those of the writer whose color vision did not seem to be defective in any way. Several normals, it will be noticed, are made use of in this paper, for the reason that at intervals the luminosity of the spectrum was changed owing doubtless to some variations of the intensity or quality of the light from the acetylene flame. The adjustments of the instruments were changed but once, the pressure of the gas was quite constant, and in addition the measurements changed also for different observers at the same time. These reasons are sufficient to assign the cause of the irregularity to some variation in the character of the light itself, and not to any inconstancy of the retinal processes. That four normal curves are used in this work is due simply to the length of time the investigation has covered; had it extended longer the number would doubtless have been increased.

The order in which the cases of color-blindness are discussed is not that in which they were examined, so that the apparently capricious manner of referring their curves to the various normals is due to grouping the cases in their natural classes. The first and second

normals are much alike, differing only in the part corresponding to the middle of the spectrum. The last two differ more widely, the readings for the fourth in particular having been made after readjustment of the apparatus.

The data for the four normals are given in the following table.

TABLE I.

NORMAL CURVES.

I		II		III		IV	
λ	Persistence.	λ	Persistence.	λ	Persistence.	λ	Persistence.
.400 μ	.0388 sec.	.400 μ	.0388 sec.	.400 μ	.0395 sec.	.405 μ	.0410 sec.
.406	.0360	.406	.0360	.412	.0365	.412	.0385
.418	.0323	.418	.0323	.439	.0268	.425	.0351
.425	.0307	.430	.0280	.472	.0196	.440	.0287
.439	.0264	.450	.0225	.495	.0157	.455	.0239
.472	.0200	.463	.0196	.520	.0135	.472	.0196
.495	.0160	.485	.0156	.550	.0126	.485	.0181
.506	.0148	.500	.0140	.588	.0126	.502	.0156
.520	.0131	.567	.0115	.640	.0143	.520	.0141
.533	.0124	.588	.0118	.720	.0243	.538	.0135
.567	.0115	.613	.0126	.730	.0260	.562	.0130
.588	.0118	.640	.0136			.588	.0126
.613	.0126	.670	.0160			.613	.0129
.640	.0136	.720	.0224			.640	.0138
.670	.0160	.730	.0240			.670	.0158
.720	.0224					.705	.0203
.730	.0240					.717	.0221
						.732	.0236
						.745	.0255

In order to see whether there was any disagreement in the measurements of the persistence of vision of persons with normal color vision, the observations necessary for the determination of their persistency curves were made by a number of my friends in the departments of psychology and physics. The results obtained by two of them are by their kind permission given here, and the measurements of the others showed substantially the same agreement. The curve shown in Fig. 1 is that obtained by Dr. Margaret Floy Washburn, and that in Fig. 2 by Mr. E. C. Roberts. These are compared with the second normal which is represented by the

dotted line in the figures. Throughout this paper the dotted curves are the normals. The data are given in Table II.

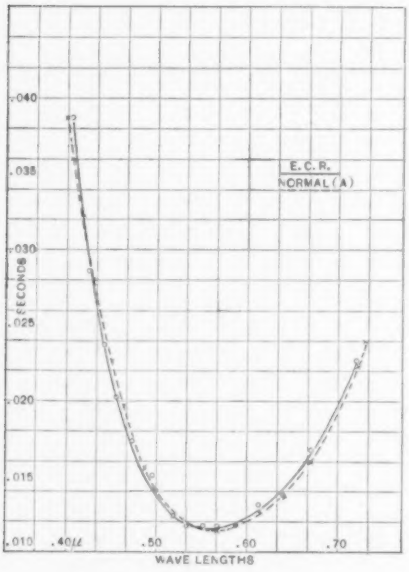


Fig. 1.

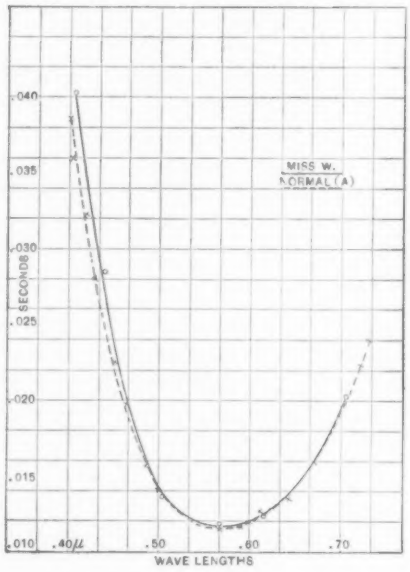


Fig. 2.

TABLE II.

Miss Washburn.		Mr. E. C. Roberts.			
λ	Persistence.	λ	Persistence.	λ	Persistence.
.406 μ	.0403 sec.	.406 μ	.0388 sec.	.533 μ	.0118 sec.
.439	.0285	.425	.0283	.550	.0117
.505	.0136	.439	.0237	.567	.0117
.567	.0118	.455	.0203	.588	.0118
.613	.0124	.472	.0173	.613	.0131
.705	.0204	.495	.0150	.640	.0137
		.520	.0123	.670	.0167
				.720	.0227

From the results obtained by these observers we may conclude that the persistence of color impressions upon the retinas of persons with normal color vision and of not widely different ages is practically the same. That a considerable disparity in age destroys this close agreement has been shown by Ferry.[1]

[1] E. S. Ferry, The Persistence of Vision, Am. Jour. Sci., Vol. 44, p. 192, 1892.

The Cases of Color-Blindness.

The twenty-six cases of color-blindness described in this paper, of which twenty-one are new, are divided into seven classes according to the form of their persistency curves. Grouping them with reference to the position of the brightest point of the spectrum would make about three subdivisions in each class. The reasons for the classification adopted will appear as the cases are examined.

Class I.

Subject No. 1.—Mr. W. O. B., when examined with the Holmgren worsteds, showed the usual indications of color-blindness. He determined his neutral point to be at $\lambda = .510\ \mu$. The persistency readings are given in Table III. In Plate I.,[1] Fig. 1, these results are shown in comparison with the second normal. Two parts of the curve are evidently abnormal, one from the beginning of the red to $\lambda = .670\ \mu$, and the other between the wave-lengths $.440\ \mu$ and $.670\ \mu$. These regions, however, differ in their meaning. The elevation above the normal *always* accompanies indications of color-blindness, while the depression signifies that to the abnormal eye the corresponding part of the spectrum is brighter than to the normal. This depression, though not found in many of the curves, is in accordance with the frequently observed phenomenon that when the retina is deficient in the power of responding to one of the fundamental sensations, the loss is somewhat compensated for by an increase in the intensity of excitation of the others.

Table III.

W. O B.

λ	Persistence.	λ	Persistence.	λ	Persistence.
.400 μ	.0420 sec.	.520 μ	.0107 sec.	.640 μ	.0128 sec.
.425	.0319	.533	.0101	.680	.0180
.455	.0204	.550	.0095	.705	.0240
.472	.0162	.567	.0096	.720	.0282
.495	.0128	.588	.0101	.730	.0324
.505	.0118	.613	.0112		

[1] The figures in *each* of the three plates are numbered from one to nine. The figures in the text are numbered independently.

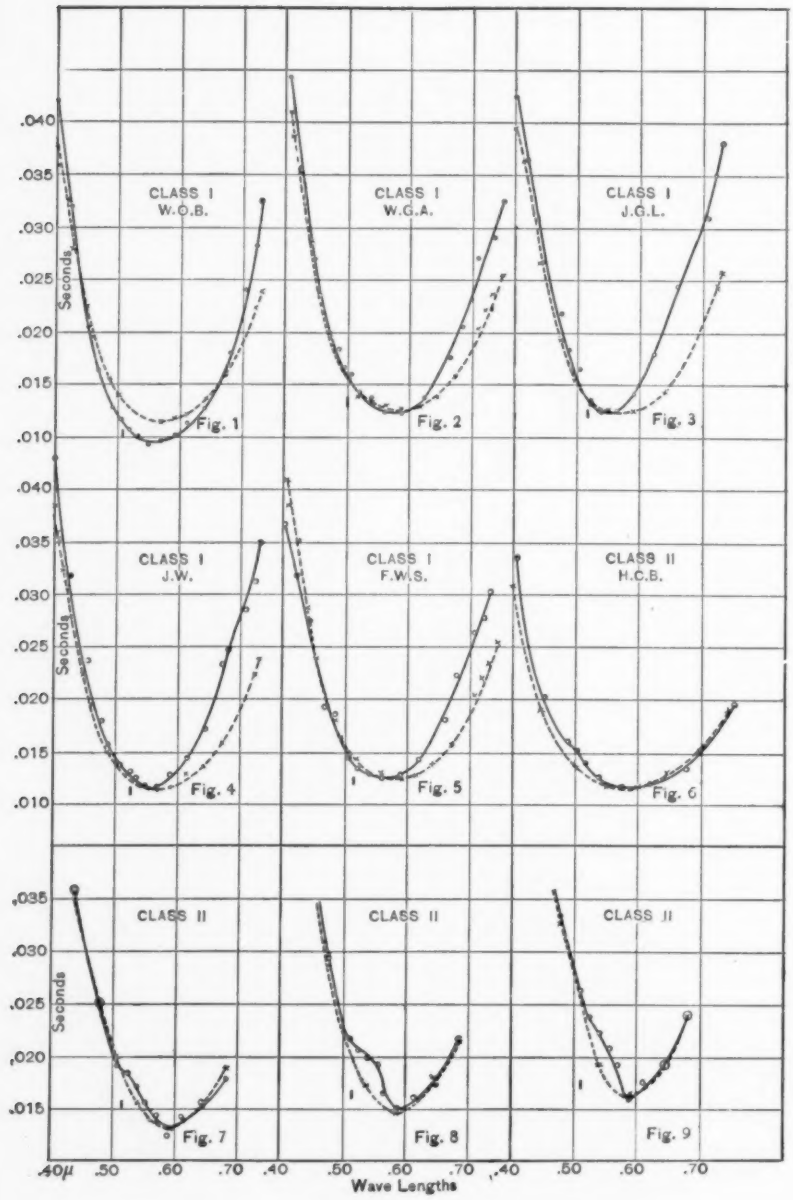

CLASS I
W.O.B.
Fig. 1
CLASS I
W.G.A.
Fig. 2
CLASS I
J.G.L.
Fig. 3
CLASS I
J.W.
Fig. 4
CLASS I
F.W.S.
Fig. 5
CLASS II
H.C.B.
Fig. 6
CLASS II
Fig. 7
CLASS II
Fig. 8
CLASS II
Fig. 9
Seconds
.040
.035
.030
.025
.020
.015
.010
.40μ
.50
.60
.70
Wave Lengths

Plate I.

The point of maximum brightness is at $\lambda = .550\ \mu$, which is a little to the green side of the normal position. The curve indicates that the part of the spectrum to which this subject is at least partially color-blind is from $\lambda = .670\ \mu$ to the end of the red.

Subject No. 2.—Mr. W. G. A., after the usual Holmgren test, located his neutral point at $\lambda = .500\ \mu$. The measurements of the persistence of the spectrum rays are given in Table IV. and are shown graphically in Plate I., Fig. 2, in comparison with the fourth normal. The curves agree throughout the violet end of the spectrum to $\lambda = .620\ \mu$ which is in the orange. From this wave-length the elevation extends to the end of the red. There is no displacement of the brightest point.

TABLE IV.

W. G. A.

λ	Persistence.	λ	Persistence.	λ	Persistence.
.405 μ	.0442 sec.	.505 μ	.0160 sec.	.660 μ	.0177 sec.
.425	.0356	.520	.0144	.680	.0207
.446	.0270	.538	.0138	.705	.0271
.472	.0200	.562	.0125	.730	.0292
.485	.0185	.588	.0124	.745	.0323
.495	.0168	.620	.0134		

Subject No. 3.—Mr. J. G. L., a graduate student in chemistry, experienced great difficulty in his spectroscopic work in the red end of the spectrum. The usual indications of color-blindness were given with the Holmgren test, and the neutral point was located at $\lambda = .515\ \mu$.

The values given in Table V. are shown in Plate I., Fig. 3, in comparison with the third normal. The agreement of the two is close up to $\lambda = .562\ \mu$, at which the elevation begins, extending thence to the end of the red. The position of the brightest point is normal.

TABLE V.

J. G. L.

λ	Persistence.	λ	Persistence.	λ	Persistence.
.400 μ	.0423 sec.	.502 μ	.0165 sec.	.620 μ	.0180 sec.
.417	.0364	.520	.0131	.660	.0245
.446	.0269	.538	.0126	.705	.0310
.472	.0218	.562	.0124	.720	.0350
.485	.0184	.588	.0141	.730	.0382

Subject No. 4. — Mr. J. W., a student in civil engineering, made the usual observations which are given in Table VI., and shown graphically in Plate I., Fig. 4, in comparison with the second normal. In the Holmgren test the green and red samples were correctly matched, but the magenta betrayed his defect. He indicated no neutral point at all clearly, but finally made a fairly good match with the white at $\lambda = .527\ \mu$. The elevation occurs in the part of the curve corresponding to the red end of the spectrum, and begins -at $\lambda = .567\ \mu$. The position of the brightest point is normal.

The last point in the violet in this and in several other curves is somewhat elevated. As exact observations in this region of the spectrum are rather difficult, little confidence can be attached to the last reading unless those immediately preceding show a similar displacement. The same remark will also apply to observations in the extreme red. Fortunately, however, in most cases, there is no uncertainty as to the character of the curve in all parts.

TABLE VI.

J. W.

λ	Persistence.	λ	Persistence.	λ	Persistence.
.400 μ	.0432 sec.	.520 μ	.0132 sec.	.640 μ	.0172 sec.
.412	.0354	.533	.0125	.670	.0234
.425	.0319	.550	.0118	.680	.0249
.455	.0237	.567	.0116	.705	.0287
.475	.0181	.588	.0130	.720	.0314
.485	.0159	.613	.0146	.730	.0350
.505	.0138				

Subject No. 5. — Mr. F. W. S., a student is one of the physical laboratories, matched the red correctly in the Holmgren test, but failed with the other two. His neutral point is at $\lambda = .515\ \mu$. The measurements tabulated in Table VII., are shown in Plate I., Fig. 5, in comparison with the fourth normal. The curve runs below the normal in the violet and also in the green. The point of maximum brightness is at $\lambda = .562\ \mu$, where the elevation begins which continues throughout the red. In this case the point of greatest brightness is shifted towards the green.

TABLE VII.

F. W. S.

λ	Persistence.	λ	Persistence.	λ	Persistence.
.405 μ	.0367 sec.	.505 μ	.0147 sec.	.660 μ	.0182 sec.
.425	.0320	.520	.0136	.680	.0223
.446	.0275	.538	.0130	.705	.0265
.472	.0195	.562	.0127	.717	.0278
.485	.0186	.588	.0130	.730	.0302
.495	.0164	.620	.0144		

The five subjects in this class have persistency curves of the same type. Two of them correctly matched one or two of the Holmgren confusion samples, while the others made mistakes with them all. With one exception their neutral points agree quite closely. With three the brightest point in the spectrum occupies its normal position, while two have it displaced toward the green.

Class II.

The subjects in this class seem to have imperfect color vision only in the green. It is rather remarkable that amomg the score of *new* cases described in this paper not one has given a curve of this type. But since at least six cases are on record, the type is well defined.

Subject No. 6. — The persistency curve shown in Plate I., Fig. 6, is that obtained by Mr. H. C. B., whose color vision is discussed in my former paper.[1] When this subject was examined no means were at hand to determine his neutral point. The elevation is but slight and is confined to the green. The position of the brightest point is normal.

Subject No. 7. — The three figures, 7, 8 and 9, shown in Plate I. are those of three similar cases investigated by Ferry, from whose paper[2] they are reproduced. In these the elevation in the green is very pronounced. The position of the brightest point is normal in each case, and the neutral points are indicated by the usual vertical lines.

[1] Allen, op. cit., Fig. 18, p. 287.
[2] Ferry, op. cit., Fig. 4, p. 204.

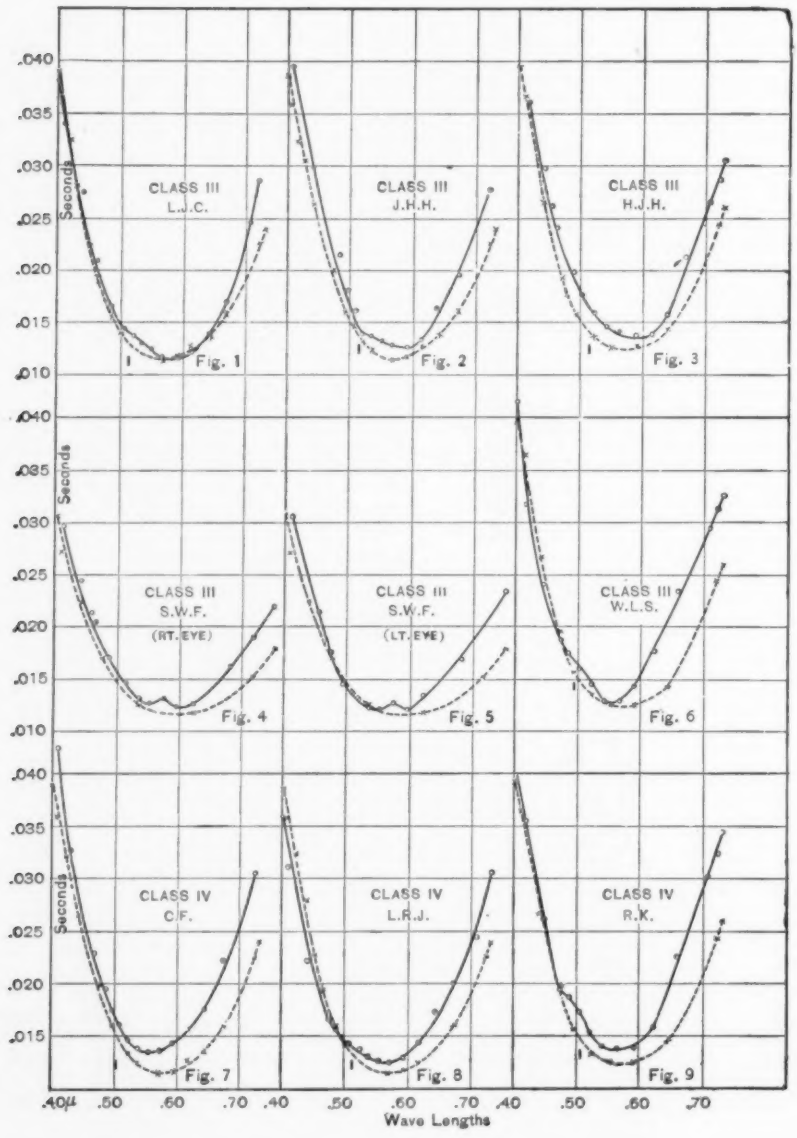

.040
.035
.030
.025
.020
.015
.010
Seconds
CLASS III
L.J.C.
Fig. 1
CLASS III
J.H.H.
Fig. 2
CLASS III
H.J.H.
Fig. 3
CLASS III
S.W.F.
(RT. EYE)
Fig. 4
CLASS III
S.W.F.
(LT. EYE)
Fig. 5
CLASS III
W.L.S.
Fig. 6
CLASS IV
C.F.
Fig. 7
CLASS IV
L.R.J.
Fig. 8
CLASS IV
R.K.
Fig. 9
.40μ .50 .60 .70 .40 .50 .60 .70 .40 .50 .60 .70
Wave Lengths

Plate II.

Class III.

Subject No. 8. — Mr. L. J. C., a student in the Engineering Department, gave decided evidences of color-blindness with the Holmgren test. His neutral point is at $\lambda = .514\ \mu$. The data in Table VIII. are shown in Plate II., Fig. 1, in comparison with the second normal. The point of maximum brightness is at $\lambda = .585\ \mu$, and, as the figure shows, is shifted a little towards the red.

The curves are practically identical through the violet and blue to $\lambda = .500\ \mu$ where an elevation begins, extending through the green to $\lambda = .570\ \mu$. Thence the curves coincide to $\lambda = .650\ \mu$, where the second elevation commences which extends to the end of the red.

TABLE VIII.

L. J. C.

λ	Persistence.	λ	Persistence.	λ	Persistence.
.400 μ	.0380 sec.	.520 μ	.0139 sec.	.613 μ	.0121 sec.
.412	.0338	.533	.0130	.640	.0138
.439	.0274	.550	.0124	.670	.0169
.463	.0209	.567	.0116	.705	.0248
.485	.0167	.588	.0115	.720	.0285
.505	.0144				

Subject No. 9. — Mr. J. H. H. was the only one of the subjects examined who was quite ignorant of his defective color vision. His first matches of the Holmgren worsted showed a very pronounced degree of color-blindness. On being told the result of the examination he was surprised and rather mortified, and requested another trial of the worsted test. This time by closely studying the samples he made a very good selection. No part of the spectrum appeared neutral to him, but he said that "green" began at $\lambda = .515\ \mu$. It is probable that this marked his neutral point, but that excessive caution prevented an unbiased judgment.

The curve, plotted from the data in Table IX., is shown in Plate II., Fig. 2, in comparison with the first normal. The brightest point is shifted toward the red. The general elevation of the whole curve indicates a diminished luminosity of the spectrum to the subject. In addition to this continuous difference between the curves, there are

two distinct elevations, one of which lies between the wave-lengths .520 μ and .590 μ, and the other from $\lambda = .615\ \mu$ to the end of the red.

TABLE IX.

J. H. H.

λ	Persistence.	λ	Persistence.	λ	Persistence
.406 μ	.0396 sec.	.520 μ	.0138 sec.	.613 μ	.0131 sec.
.440	.0299	.533	.0136	.640	.0162
.483	.0215	.550	.0131	.670	.0196
.495	.0180	.567	.0128	.720	.0276
.505	.0161	.588	.0126		

Subject No. 10. — Mr. H. J. H. located his neutral point at $\lambda = .515\ \mu$. The persistency measurements of Table X. are shown in Plate II., Fig. 3, in comparison with the third normal. This curve is not as pronounced in its characteristics as the previous ones. The last reading in the extreme violet has been neglected for reasons stated in a similar case. The relative positions of the curves indicate diminished luminosity of the whole spectrum to the subject. The first elevation lies between the wave-lengths .500 μ and .600 μ, the second extends from .630 μ to the end of the red. The region of greatest brightness is shifted toward the red and located at $\lambda = .600\ \mu$ which is the point of separation of the two elevations.

TABLE X.

H. J. H.

λ	Persistence.	λ	Persistence.	λ	Persistence.
.400 μ	.0500 sec.	.502 μ	.0178 sec.	.640 μ	.0157 sec.
.417	.0360	.520	.0158	.670	.0211
.440	.0298	.538	.0146	.705	.0262
.450	.0261	.562	.0141	.720	.0283
.460	.0240	.588	.0137	.730	.0305
.485	.0199	.613	.0137		

Subject No. 11. — In my former paper[1] on color vision there was described a case of color-blindness, Mr. S. W. F., which belongs to this class, and whose persistency curves are reproduced in Plate II.,

[1] Allen, op. cit., Fig. 15, p. 284.

Figs. 4 and 5. He was unable to find any neutral point, though he divided the spectrum into "yellow" and "blue" at $\lambda = .510\ \mu$. The figures show that there are two elevations separated by the point of maximum brightness at $\lambda = .600\ \mu$.

Subject No. 12. — Mr. W. L. S. made correct matches with the red sample in the Holmgren test, but failed with the others. The neutral point seemed difficult to decide upon, but he finally selected a part of the spectrum about $\lambda = .495\ \mu$. The brightest point, located at $\lambda = .550\ \mu$, is shifted toward the green, and, as is usual in curves of this type, separates the elevations.

The persistency measurements of Table XI. are compared with the third normal in Plate II., Fig. 6. In the violet and blue the curves are almost identical. One of the two elevations occurs in the green from $\lambda = .485\ \mu$ to $\lambda = .538\ \mu$, and the other from $\lambda = .560\ \mu$ to the end. The point of maximum brightness is shifted toward the green.

TABLE XI.

W. L. S.

λ	Persistence.	λ	Persistence.	λ	Persistence.
.400 μ	.0413 sec.	.502 μ	.0160 sec.	.620 μ	.0176 sec.
.417	.0318	.520	.0146	.660	.0233
.446	.0241	.538	.0130	.705	.0292
.472	.0188	.562	.0129	.720	.0311
.485	.0173	.588	.0142	.730	.0325

The persistency curves of this class have two elevations, one in the red and the other in the green region, the exact boundaries differing in the various cases. The first three have the same neutral point, and the brightest point is shifted toward the red. The fourth case has a slightly different neutral region and the position of the brightest point is normal. The last case has a decidedly different neutral point, occurring farther in the blue than usual, and the brightest point is displaced towards the green.

Class IV.

Subject No. 13. — Mr. C. F., a gentleman experienced in making very exact measurements in engineering work and also in astronomy, kindly consented to make observations for the determination of his

persistency curve. His neutral point is at $\lambda = .502\ \mu$. With the Holmgren worsteds he showed many indications of color-blindness, but was able to select some colors correctly, especially saturated reds, among those that were in the range of his defective color perception. The persistency curve is shown in Plate II., Fig. 7, in comparison with the first normal. To this subject the whole spectrum appears less luminous than normal. The brightest point is shifted toward the green. There is but one elevation which extends from the neutral point over the entire red end.

TABLE XII.

C. F.

λ	Persistence.	λ	Persistence.	λ	Persistence.
.406 μ	.0424 sec.	.505 μ	.0160 sec.	.588 μ	.0142 sec.
.425	.0328	.520	.0146	.613	.0156
.463	.0228	.533	.0138	.640	.0176
.483	.0194	.550	.0135	.670	.0222
.495	.0173	.567	.0136	.720	.0306

Subject No. 14.—Mr. L. R. J. could hardly be persuaded to try the Holmgren test, remarking that the pile of worsteds was hopelessly confusing. Some selections that he did make, however, were correct, but most of them indicated a decidedly defective perception of color. His neutral point is at $\lambda = .510\ \mu$. The persistency measurements in Table XIII., are shown graphically in Plate II., Fig. 8, compared with the second normal. Their relative positions in the violet and blue show that the part of the spectrum up to $\lambda = .490\ \mu$ is more than normally luminous, while from this wave-length to the end of the red there is the usual elevation indicative of corresponding visual disturbances. The position of the brightest point is normal.

TABLE XIII.

L. R. J.

λ	Persistence.	λ	Persistence.	λ	Persistence.
.400 μ	.0362 sec.	.505 μ	.0142 sec.	.613 μ	.0144 sec.
.412	.0312	.520	.0137	.640	.0172
.439	.0222	.533	.0131	.670	.0200
.472	.0166	.550	.0127	.705	.0246
.485	.0154	.567	.0125	.720	.0265
.495	.0149	.588	.0129	.730	.0306

Subject No. 15. — Mr. R. K., the last subject in this class, displayed with the worsteds an unusually great degree of color-blindness. His neutral point is at $\lambda = .503\ \mu$. The persistency readings given in Table XIV. are shown in Plate II., Fig. 9, in comparison with the third normal. An examination of the figure shows that his color vision is normal through the violet to about the middle of the blue, $\lambda = .470\ \mu$, from which point the curves diverge, indicating defective color perception throughout the remainder of the spectrum. The position of the brightest region is normal. The last reading in the extreme violet has been neglected for the same reasons that were stated in a previous case.

The characteristic feature of this class is that the persistency curve on the violet side of the neutral point is normal and on the red side abnormal, the neutral region forming the dividing line.

TABLE XIV.

R. K.

λ	Persistence.	λ	Persistence.	λ	Persistence.
.400 μ	.0489 sec.	.502 μ	.0172 sec.	.620 μ	.0157 sec.
.417	.0355	.520	.0152	.660	.0223
.446	.0261	.538	.0140	.705	.0301
.472	.0195	.562	.0138	.720	.0323
.485	.0185	.588	.0139	.730	.0343

Class V.

The relatively large number of cases in this class indicates that it is probably the most common type of color-blindness. The characteristics of the persistency curves are two elevations occurring in the red and violet, the intervening portions being normal. Three of the seven cases have the position of the brightest point unaltered; two have it shifted toward the green and two toward the red.

Subject No. 16. — Mr. J. P. K. gave pronounced evidences of color-blindness with the Holmgren test. His neutral point is at $\lambda = .511\ \mu$. The persistency measurements in Table XV. are shown in Plate III., Fig. 1, in comparison with the fourth normal. In no part do the curves coincide. There is an elevation in the violet extending to $\lambda = .470\ \mu$ and a similar one from $\lambda = .720\ \mu$ to

the end of the red. The depression of the curve between these elevations indicates an increased brightness of the spectrum to the subject. The position of the brightest point is normal.

TABLE XV.

J. P. K.

λ	Persistence.	λ	Persistence.	λ	Persistence.
.405 μ	.0485 sec.	.501 μ	.0154 sec.	.660 μ	.0145 sec.
.412	.0450	.520	.0132	.680	.0175
.425	.0400	.538	.0125	.705	.0212
.440	.0338	.562	.0117	.717	.0227
.455	.0284	.588	.0113	.730	.0262
.472	.0215	.620	.0119	.745	.0290
.487	.0200				

Subject No. 17. — Mr. J. B. K. made nearly all the mistakes possible in the Holmgren test. His neutral point is at $\lambda = .514\ \mu$. The persistency measurements given in Table XVI. are shown in Plate III., Fig. 2, in comparison with the first normal. The position of the brightest point is shifted toward the red. In other respects this curve is similar to the preceding one.

TABLE XVI.

J. B. K.

λ	ersistence.	λ	Persistence.	λ	Persistence.
.400 μ	.0497 μ	.505 μ	.0133 sec.	.640 μ	.0125 sec.
.406	.0444	.520	.0120	.670	.0160
.412	.0412	.533	.0113	.680	.0180
.439	.0287	.550	.0109	.705	.0220
.463	.0208	.567	.0106	.720	.0247
.483	.0175	.588	.0104	.730	.0300
.495	.0148	.613	.0109		

Subject No. 18. — Mr. R. L. K. in the Holmgren test matched the red and green samples correctly but failed with the third. The only part of the spectrum that seemed to him neutral was at $\lambda = .583\ \mu$, which is the wave-length at which König's red and green sensation curves intersect, and where, under some circumstances, a neutral point might be expected to occur. The data of Table XVII. are shown in Plate III., Fig. 3, in comparison with the first normal. The brightest point is in its normal position. The curves coincide between the two elevations.

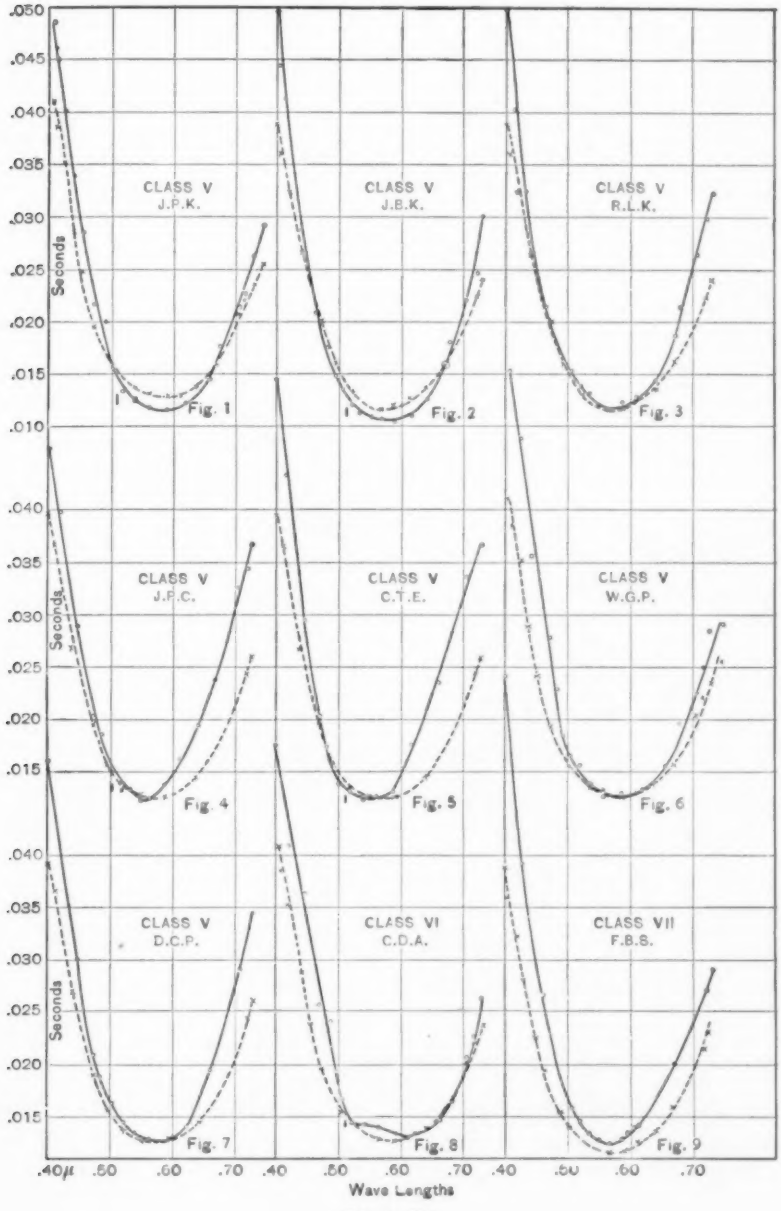

CLASS V
J.P.K.
Fig. 1
CLASS V
J.B.K.
Fig. 2
CLASS V
R.L.K.
Fig. 3
CLASS V
J.P.C.
Fig. 4
CLASS V
C.T.E.
Fig. 5
CLASS V
W.G.P.
Fig. 6
CLASS V
D.C.P.
Fig. 7
CLASS VI
C.D.A.
Fig. 8
CLASS VII
F.B.S.
Fig. 9
Seconds
.050
.045
.040
.035
.030
.025
.020
.015
.010
.40μ .50 .60 .70
Wave Lengths

Plate III.

TABLE XVII.
R. L. K.

λ	Persistence.	λ	Persistence.	λ	Persistence.
.400 μ	.0499 sec.	.533 μ	.0130 sec.	.670 μ	.0184 sec.
.412	.0402	.550	.0120	.680	.0214
.430	.0324	.567	.0116	.705	.0266
.463	.0212	.588	.0123	.720	.0299
.505	.0152	.613	.0127	.730	.0321
.520	.0138	.640	.0142		

Subject No. 19. — Mr. J. P. C. made incorrect selections with all the Holmgren test samples. His neutral point is at $\lambda = .506\,\mu$. The persistency measurements are given in Table XVIII. and are shown in Plate III., Fig. 4. The curve shows that the brightest point is shifted slightly towards the green. There are the two characteristic elevations, one in the violet and the other in the part corresponding to red, orange and yellow. The curves coincide in the green.

TABLE XVIII.
J. P. C.

λ	Persistence.	λ	Persistence.	λ	Persistence.
.400 μ	.0457 sec.	.520 μ	.0139 sec.	.640 μ	.0194 sec.
.418	.0397	.533	.0132	.670	.0235
.447	.0287	.550	.0123	.705	.0324
.472	.0202	.567	.0123	.720	.0344
.485	.0184	.588	.0135	.730	.0366
.502	.0149	.613	.0162		

Subject No. 20. — Mr. C. J. E. determined his neutral point to be at $\lambda = .516\,\mu$. His persistency curve is shown in Plate III., Fig. 5, in comparison with the third normal. The brightest point is shifted toward the green. The curves coincide between the elevations. The following table contains the persistency measurements of this subject.

TABLE XIX.
C. T. E.

λ	Persistence.	λ	Persistence.	λ	Persistence.
.400 μ	.0526 sec.	.502 μ	.0140 sec.	.620 μ	.0177 sec.
.417	.0433	.520	.0131	.660	.0235
.446	.0292	.538	.0125	.705	.0335
.472	.0202	.562	.0125	.730	.0368
.485	.0174	.588	.0129		

Subject No. 21. — Mr. W. G. P., a student in one of the physical laboratories, gave very few indications of color-blindness with the Holmgren test, the only color which betrayed his defective vision being the green. No neutral point was found except a rather doubtful region in the neighborhood of $\lambda = .560\,\mu$. Three independent settings of the instrument were made at this point. The readings in Table XX. are shown in Plate III., Fig. 6, in comparison with the fourth normal.

TABLE XX.

W. G. P.

λ	Persistence.	λ	Persistence.	λ	Persistence.
.405 μ	.0532 sec.	.505 μ	.0167 sec.	.660 μ	.0155 sec.
.425	.0469	.520	.0155	.680	.0197
.446	.0357	.538	.0138	.705	.0226
.472	.0279	.562	.0127	.717	.0250
.485	.0228	.588	.0128	.730	.0284
.495	.0185	.620	.0131	.745	.0292

Subject No. 22. — Mr. D. C. P. matched correctly the red and green samples, but failed with the magenta. He could find no neutral point at all. The persistency values in Table XXI. are shown in Plate III., Fig. 7, compared with the third normal. The point of maximum brightness is shifted toward the red.

TABLE XXI.

D. C. P.

λ	Persistence.	λ	Persistence.	λ	Persistence.
.400 μ	.0488 sec.	.520 μ	.0142 sec.	.620 μ	.0136 sec.
.447	.0300	.538	.0134	.660	.0193
.472	.0208	.562	.0126	.705	.0287
.485	.0185	.588	.0125	.730	.0344
.502	.0162				

Class VI.

Subject No. 23. — Only one subject belonging to this class was among the number of color-blind persons examined. Mr. C. D. A., the subject in question, failed in the Holmgren test with the

green confusion sample only, and remarked that he always had trouble in distinguishing between green and brown. His neutral point is at $\lambda = .512\ \mu$, and is peculiar as being the point of coincidence of the curves, and lies between the two elevations. The persistency data are in Table XXII., and are shown in Plate III., Fig. 8, in comparison with the fourth normal. The point of maximum brightness is considerably displaced towards the red, occurring at $\lambda = .620\ \mu$. One elevation of the curve runs from the extreme violet through the blue and is terminated in the green by the neutral region; the second extends from this region to the wave-length denoting the brightest point. The curves thence coincide to nearly the end of the red, where the last reading is a little elevated. As the extreme red is difficult to observe accurately, this slight elevation is to be regarded as very doubtful.

TABLE XXII.

C. D. A.

λ	Persistence.	λ	Persistence.	λ	Persistence.
.405 μ	.0508 sec.	.505 μ	.0164 sec.	.660 μ	.0148 sec.
.425	.0410	.520	.0145	.680	.0165
.446	.0363	.538	.0142	.705	.0206
.472	.0256	.562	.0139	.717	.0226
.485	.0240	.588	.0135	.730	.0262
.495	.0192	.620	.0132		

Class VII.

A Case of Total Color-blindness.

Subject No. 24. — Mr. F. B. S., a student in the Veterinary Department of the University, was noticed by one of the instructors in chemistry to make many mistakes in naming the characteristic colors of chemical reactions. Through the kindness of Dr. Turner of the Chemistry Department, the case was brought to my attention and the consent of the student gained to make several color vision tests. The subject himself stated that all "colors" were equally difficult to distinguish and that all the Holmgren worsteds were about the same to him.

Inquiry at various times elicited the following personal information: Near objects are distinguished much better than those at a

greater distance. Vision can be fixated on a point for some time, but a feeling of fatigue is soon experienced which often is painful. On leaving a room and going out into the bright sunshine the light hurts his eyes occasioning an excessive flow of tears. At intervals of about half a year he has severe headaches which are accompanied by hemiopsy or "half vision," a peculiarity which also troubles one of his sisters. On two occasions complete blindness lasting several hours came gradually upon him, once when in high school and the other time during a lecture at the university. During these periods of blindness only sufficient visual power was retained to distinguish light from darkness. The pupil, he said, always dilates during these "blind intervals." As all glasses he had ever used seemed to hurt his eyes he had discontinued their use. No other member of his family or of his relatives was affected with visual trouble of any kind as far as he knew, except his sister in the way mentioned.

Very complete series of selections of the Holmgren worsteds were made, which, upon examination through suitable colored glasses, proved to be matched according to their brightness. With a light gray sample he matched light shades of very many colors. He had learned, he said, to distinguish yellow, though this was sometimes confused with neutral shades. These indications all confirmed the conclusion that his vision was achromatic, and the proof will appear complete when the various curves he obtained are examined.

As all the spectrum was supposed to appear colorless to him and to vary only in brightness, the Helmholtz color-mixing spectrophotometer, adapted for the determination of neutral points as previously described, was used to obtain a luminosity curve. This was easily done by varying the intensity of the reflected light with the Nicol prism until it matched the part of the spectrum under observation. In this way white light of some intensity was matched with every part of the spectrum. Three or four independent observations were made at each selected point and readings taken of the angle between the principal planes of the polarizer and analyzer, to the square of the cosine of which the intensity of the light is proportional. The mean values of these angles are given in the following table.

TABLE XXIII.

F. B. S. LUMINOSITY CURVE.

λ	Angle Between Planes = α	cos² α	λ	Angle Between Planes = α	cos² α
.450 μ	88° 12′	.0009	.563 μ	71° 42′	.098
.457	87 0	.0027	.571	69 0	.128
.466	85 54	.0051	.582	66 12	.163
.475	85 0	.0076	.593	63 36	.197
.485	83 12	.0140	.605	62 30	.213
.498	81 42	.0208	.616	72 6	.094
.510	80 0	.0301	.628	76 36	.054
.524	78 30	.0398	.640	82 18	.018
.537	77 18	.0482	.655	84 18	.009
.545	75 36	.062	.670	85 48	.005
.554	73 36	.080	.685	87 54	.0009

These values, plotted in Fig. 3, give the usual form of luminosity curve. One very remarkable feature is that the maximum occurs

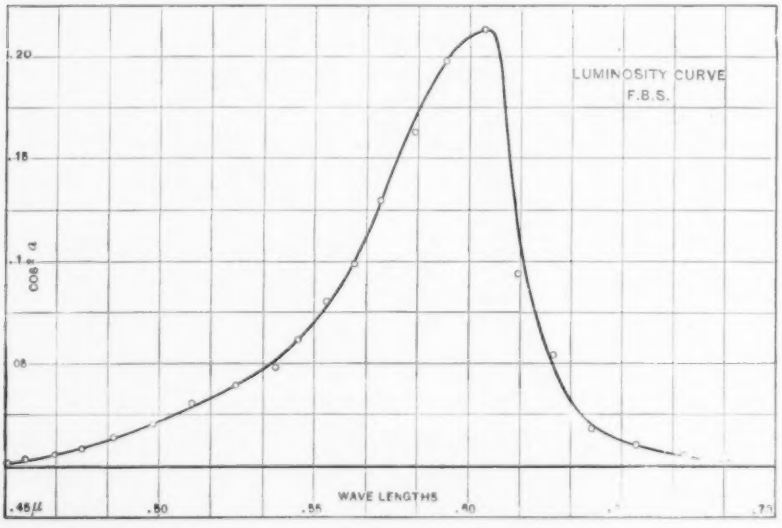


Fig. 3.

at $\lambda = .605\ \mu$, or is practically normal; usually it is found at the line E ($\lambda = .527\ \mu$), and Abney[1] in particular has studied several cases

[1] Sir W. de W. Abney, "A Case of Monochromatic Vision," Proc. Roy. Soc., Vol. 66, 1900, p. 179. Also Color Vision (Tyndall Lectures), Chap. 12, p. 148.

in which the maximum luminosity is so displaced. The line E is also the normal maximum brightness when the intensity of the spectrum is so much reduced that all color disappears, leaving only a substratum of gray. The coincidence of the luminosity maximum of the faint light spectrum to the normal eye with that of the normal spectrum to the totally color-blind retina is of much theoretical interest. In this case, however, the agreement does not occur.

Persistency curves were also obtained for both eyes, but since they agree completely only one is here given, the data for which are recorded in Table XXIV. The curve is shown in Plate III., Fig. 9, in comparison with the second normal. Readings were taken, it will be observed, at points very close together through the yellow and green in order to see if there were any indications of three separate elevations as might be expected from any trichromatic theory. The curve, however, is simply elevated throughout its entire extent, the increase in the duration of color impressions varying from a maximum in the violet to a minimum in the yellow, the increase in the red being intermediate in value.

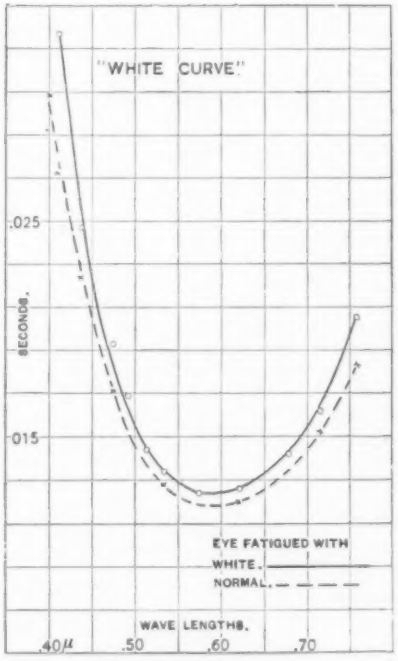


Fig. 4.

Both curves have their lowest point at $\lambda = .570\,\mu$ which indicates that the region of greatest brightness is not shifted. The luminosity curve showed the brightest point to be at $\lambda = .605\,\mu$. Direct observation located it at $\lambda = .570\,\mu$. The three determinations should agree, though the cause of the variation may be in the difference between the spectra upon which the two sets of measurements were made. The spectrum used for persistency observations was much more highly dispersed than the one by

which the luminosity curve was obtained. If the brightest point is shifted, the displacement in any case is but little.

In my former paper on color vision to which reference has already been made, there was described an experiment in which the normal eye was fatigued with white light and a persistency curve obtained with it in this condition. The effect of this fatigue was to diminish the sensitiveness of the retina for all colors. The curve showing this effect is reproduced in Fig. 4. The similarily of this figure with that (Plate III., Fig. 9) showing the measurements of the totally color-blind person is very apparent.

TABLE XXIV.

F. B. S.

λ	Persistence.	λ	Persistence.	λ	Persistence.
.400 μ	.0570 sec.	.533 μ	.0134 sec.	.605 μ	.0138 sec.
.430	.0391	.550	.0127	.613	.0142
.463	.0264	.567	.0124	.670	.0200
.505	.0159	.588	.0128	.720	.0270
.520	.0145	.597	.0133	.730	.0288

DISCUSSION OF THE SYSTEM OF CLASSIFICATION.

The regularity of the curves and the general uniformity of the measurements which have been examined in the preceding pages naturally excite in one a feeling of confidence in their reliability, a feeling which is deepened by the almost ideal manner in which the results permit themselves to be classified. And yet, strange as it may seem upon reflection, considerable criticism has been levelled at the persistency of vision method of studying the phenomena of color perception on account of this very uniformity of the observations. It has been gravely asserted that the eye is such a delicate organ, troubled by so many imperfections, and the measurements themselves subject to so many sources of error, that constancy of duration of visual impressions is impossible to realize. Undoubtedly there are sources of error which affect the results, but they must enter to an equal extent in observations in all parts of the spectrum; and as the conclusions are drawn from a *comparison* only of the results obtained by normal and by abnormal eyes under exactly similar conditions, the effect of these errors must be vanishingly small.

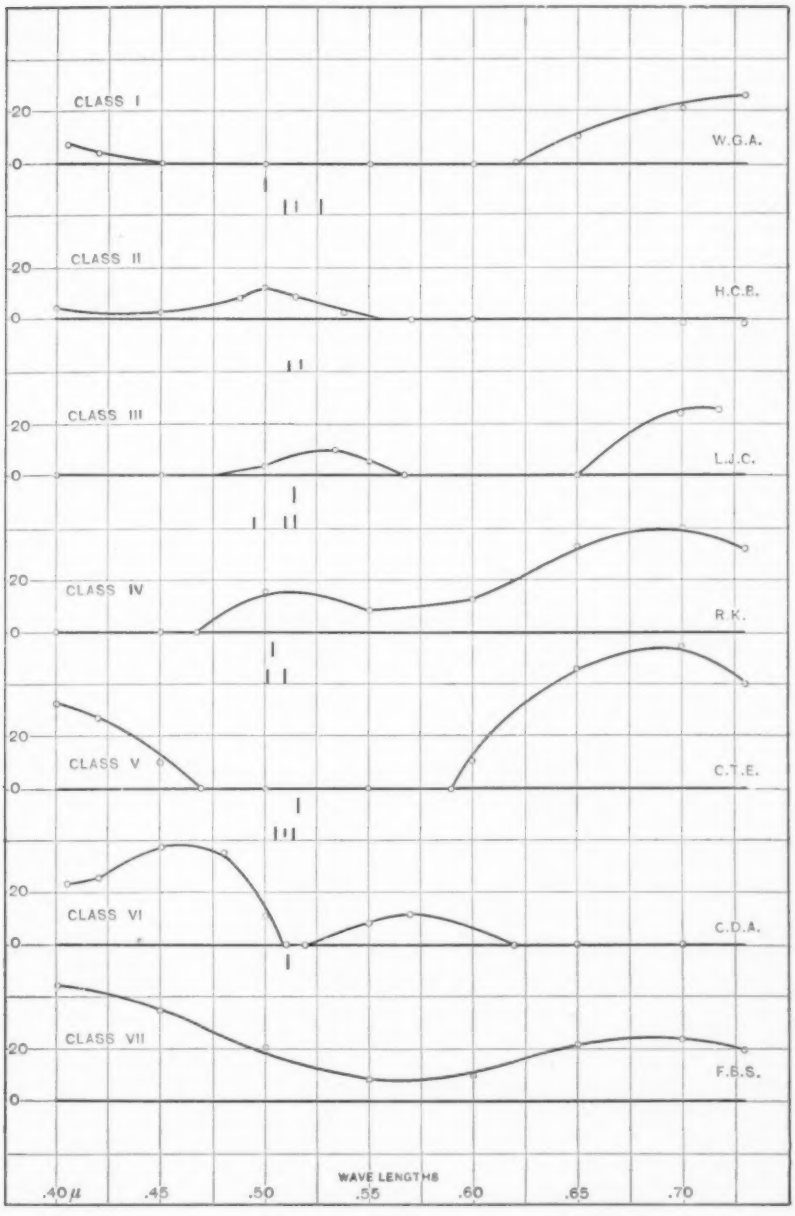

CLASS I
W.G.A.
CLASS II
H.C.B.
CLASS III
L.J.C.
CLASS IV
R.K.
CLASS V
C.T.E.
CLASS VI
C.D.A.
CLASS VII
F.B.S.
20
0
WAVE LENGTHS
.40μ
.45
.50
.55
.60
.65
.70

Fig. 5.

The criticism affects far more than the results discussed in this paper. The experiments of Abney and of König, as well as those of numerous other investigations in the domain of color vision, are equally discredited. And indeed the acceptance of the standpoint of this criticism would put a stop to further exact experiments in this branch of science. If experimental evidence is allowed its rightful precedence over theory this criticism becomes of no effect.

Attention has been directed to the general results of the Holmgren test with the subjects considered in this paper. Some failed with all the test samples, others with two, and others still with but one. The Holmgren test, valuable as it is for the rapid detection of color-blindness, is manifestly a very inaccurate method of classifying the cases. Those who are aware of their visual imperfections are able from experience to avoid many indications of their condition. Other tests than this are generally used to provide a basis of classification, such, for example, as the location of the neutral region or of the point of maximum brightness.

For the general discussion of the results which have been considered in detail, one curve of each of the seven classes is shown in Fig. 5 so that they may be readily compared. In this figure the normal curve is everywhere reduced to the same ordinate making that curve a straight horizontal line. The abnormal curves[1] are reduced in the same ratio thus permitting their characteristics to be more strikingly shown.

This method of representation has the additional merit of enabling the mutual relationship of the classes of curves, and therefore of the divisions of color-blindness, to be comprehended in one figure. Though we cannot yet determine the full meaning of the abnormal persistency curve, yet it has been seen that certain parts agree with the normal and other parts disagree in a thoroughly systematic manner. The elevations, being a sure accompaniment of color-blindness, must be characteristic of it. But that some parts of the curve are normal cannot necessarily imply that the corresponding portions of the spectrum are always perceived normally, for the

[1] In Fig. 5 the neutral point of the subject whose curve is shown is represented by the vertical line standing alone. The neutral points of the other subjects of the class are marked by similar lines below the other.

neutral region, which as its name indicates is devoid of color, very often occurs in the normal part of the curve. Indeed in one case (*C*, *D*, *A*, Plate III., Fig. 8) the neutral point is the only normal part between the two elevations. The persistency curve shows the variation of the perception of brightness of the spectrum, and involves color only in so far as it is connected with the sensation of brightness.

A brief summary of the characteristics of the classes of curves is given as follows:

Class I. — Curves have one elevation which occurs in the part corresponding to red and orange, the rest of the curve being normal.

Class II. — Curves have one elevation in the part corresponding to the green region, extending into the yellow and blue.

Class III. is a combination of the first two classes. Curves have two elevations, one in the red and the other in the green, separated by a normal portion.

Class IV. is a modification of the third class. The curves have one elevation extending over all the region from the beginning of the green on the violet side to the end of the red.

Class V. — Curves have two elevations, one in the red and the other in the violet, the intervening portion being normal.

Class VI. — Curve has two elevations, one in the green and the other in the violet.

Class VII. — The whole curve is elevated above the normal.

In the different classes corresponding elevations do not always extend over the same portion of the spectrum. The elevation in the red sometimes covers the orange and even yellow. The elevation in the green is sometimes shifted very much towards the yellow, and the limits of the violet elevation also vary to some extent. These peculiarities do not, however, invalidate the general conclusions; for color-blindness may be characterized by a modification of the color apparatus as well as by the absence of one or more of the primary sensations, and this may easily result in the variation of the position of the elevations.

Bearing of the Curves on Color Theories.

The Hering theory of color vision postulates two pairs of antagonistic color processes, one resulting in the red and green sensations,

the other in the yellow and blue. Any modification of the red or yellow sensations must be accompanied by a modification of the green and blue respectively. It therefore follows that red or green color-blindness cannot exist alone. Both sensations are normal together or both abnormal. From the theory yellow-blue blindness is possible, though some consider it very improbable.

From the standpoint of this hypothesis there are three possible types of persistency curves: one in which elevations would occur in the red and green portions, a second in which they would occur in the yellow and blue, and the third in which the whole curve would be elevated. Curves with single elevations in any part are directly opposed to the provisions of the theory in question. The curves comprising the third, sixth and seventh classes may be considered to be in harmony with the theory, the remainder are impossible to be accounted for by it.

The same objections obtain with the other hypotheses of color vision which are mere modifications of Hering's or constructed by analogy with it, such as, for example, the theory of Müller and that of Ebbinghaus. To many of the minor theories which have been devised in such abundance, application of these results is perhaps needless.

Turning our attention from four-color to three-color theories, the case is at once seen to be very different. In this connection the classification may be advantageously discussed from the standpoint of the Young-Helmholtz theory. From the number of fundamental color sensations and their independent character, the possible types of abnormal persistency curves may be determined. Any of the three primaries, red, green or violet may be absent or modified separately because of their independence. The resulting persistency curves would show the defect by a single elevation in the part of the curve corresponding to those light waves to which the retina is not normally responsive. For it has been repeatedly shown that the luminosity curves of the color-blind indicate decreased brightness of certain parts of the spectrum, which in the persistency curve shows itself by one or two elevations.

The Young-Helmholtz theory also admits the possibility of types of color-blindness in which two sensations are simultaneously modi-

fied or lacking, the absent ones being red and green, red and violet, or green and violet. The persistency curves corresponding to each of these cases would have two elevations appropriately situated.

The original form of the theory not admitting the possibility of total color-blindness, its experimental demonstration has necessitated some modification. Adopting the modern form of the theory, one is led to the conclusion that there may be anticipated types of persistency curves corresponding to the seven possible cases of color-blindness described. Curves corresponding to six of these types have been obtained and described in this paper, the missing one being that in which one elevation would occur in the violet. No case of violet-blindness was found among the subjects examined, though Abney[1] has described one.

The curves in this paper it will be remembered have been grouped into seven classes, but III. and IV. are perhaps essentially the same.

With the general provisions of the Franklin theory, which now has its champions in the lists, these experiments are also in harmony, except in the selection of blue instead of violet for one of its triad of fundamentals.

The twenty-six cases of color-blindness which have been discussed comprise comparatively few who have defective color perception confined to one sensation. Most of them have red-blindness in some degree combined with either green- or violet-blindness, the majority falling into the latter division. Since abnormal perception of green or red separately is comparatively infrequent, there is a good basis for Hering's conclusion that red- and green-blindness are always associated together. Though this is partially correct, a statement nearer the truth is that red-blindness is nearly always associated with a similar defect in either violet or green, more commonly the former.

The study of the phenomena of color vision by the method of the persistence of visual impression sheds no light apparently on the nature of the retinal processes themselves. Whether they are concerned with nerve fibrils, photo-chemical substances, the mechanical tearing down of complex color molecules, or with any other of the numerous devices for transforming certain radiant energy into sub-

[1] "Colour Vision," p. 73.

jective color sensation, the method is not competent to decide. Nor does it afford any explanation of after-images, contrast colors, fields of color, and the numerous other phenomena of chromatic vision which all contribute to make the subject of color perception so peculiarly elusive. While all these demand explanation and incorporation into acceptable theories, no less do the very striking characteristics of the persistency curves, intimately associated as they undoubtedly are with abnormal color vision.

The curves, more especially those obtained by the totally color-blind subject, seem to show quite definitely the existence of an underlying white sensation. Color, whatever else it may be, manifests itself in part as an added luminosity to the fundamental white. When some one color process is not present in the retina, or is present in a modified form, the part of the spectrum which would be its normal stimulus, is perceived less intensely, and the persistency curve through this region is that of the underlying white alone, or of white mingled with traces of the fading color sensation, which gives it the familiar elevated appearance. So that while the physiological processes involved are very obscure, yet the uniformity of location of the elevations seems to have almost a determining influence upon the choice of red, green and violet as the color fundamentals.

Some of the more important conclusions which seem to be justified by the general character of the results which have been examined may be conveniently collected here.

1. Persons with normal color vision, and of not widely different ages, have the same persistency curve under similar circumstances; or, all color impressions have the same duration in their retinas.

2. The persistency curves of the color-blind always have characteristic elevations, either one or two in number, which occur in general in those portions of the curves corresponding to the red, green and violet in the spectrum.

3. On the basis of the modified form of the Young-Helmholtz theory there are seven possible types of color-blindness: those in which only one of the primaries is absent or modified, those in which any two may be simultaneously absent or modified, and total color-blindness. Persistency curves corresponding to six of

these types have been described in this paper, none having been obtained to illustrate violet-blindness.

4. The results are entirely opposed to the assumption of four fundamental color sensations, but are in harmony with the selection of red, green and violet as primaries. The existence of a white sensation is also to be inferred, and that color consists, in part at least, of an additional brightness superposed upon this underlying white.

In an investigation of this kind I am necessarily under great obligations to many persons. Without the courteous coöperation of those who have shown such interest and patience in making the careful observations discussed in these pages, the successful prosecution of the work would have been impossible. In particular Dr. Margaret Floy Washburn and Mr. E. C. Roberts have obtained for me important results which have been referred to in their place. To Professor E. L. Nichols, whose method of studying the effects of light upon the retina has been followed, and under whose direction the research was carried on, I am indebted for numerous suggestions which have been incorporated in the work.

PHYSICAL LABORATORY,
CORNELL UNIVERSITY, May, 1902.

INTERFERENCE IN THIN FILMS—A GRAPHICAL TREATMENT.

BY E. R. DREW.

WHEN light falls upon a thin film of a transparent substance, interference fringes are observed in the portions of light reflected from the two surfaces. These fringes, under given conditions, appear to be localized at a particular place, so that they are not seen distinctly with a telescope unless it is focused upon a point at a particular distance from the film. This feature of the phenomenon of interference due to thin films has seemed rather difficult of explanation.

Michelson[1] has given a mathematical solution of the problem for the cases which arise in the form of interferometer devised by him, in which the light is always incident normally or nearly so; and Feussner[2] has given an elaborate treatment of the general case of light incident at any angle upon a film whose plane surfaces make a small angle with each other. More recently H. A. Pocklington[3] has proposed a method of analysis which is much simpler and clearer than that of Feussner.

It has seemed to the writer that it might be an aid to clearness of thought with regard to the whole phenomenon if it could be treated in a graphical way, by which the wave-surfaces could be constructed, and the interference effects obtained by the intersections of these surfaces.

The method is often used in making clear some simple cases of interference, as, for instance, the effects which are seen when a distant arc light is viewed through two pinholes close together in a card which is held just in front of the eye. In this case each pinhole becomes effectively a source of light, sending out disturbances

[1] Winkelmann, Handbuch der Physik, II., 1, p. 546.
[2] Phil. Mag. (5), 13, p. 236, 1882.
[3] Proc. Camb. Phil. Soc., XI., 2, p. 105, April, 1901.

in the form of spherical waves into the region behind the card. The waves in the two sets are similar in every respect, having come from the same actual source, and so are able to produce definite interference effects.

In Fig. 1, A and B represent these two effective sources, and the circular arcs represent a series of corresponding wave-fronts of the two systems of waves. Any point in which a wave-front of system A intersects one of system B is evidently a point of maximum disturbance; and as the wave-fronts move outward, all points on the loci of these intersections will be points of maximum disturbance continuously. These loci are obviously portions of a system of hyperbolas, having A and B as foci; but within the region considered their curvature is so small that they may be well enough represented by straight lines. If a screen be placed within this region, so that the light passing through the two pinholes falls upon it, there will be a maximum of intensity at each point where it is cut by one of these lines. In this case the fringes have no definite focus.

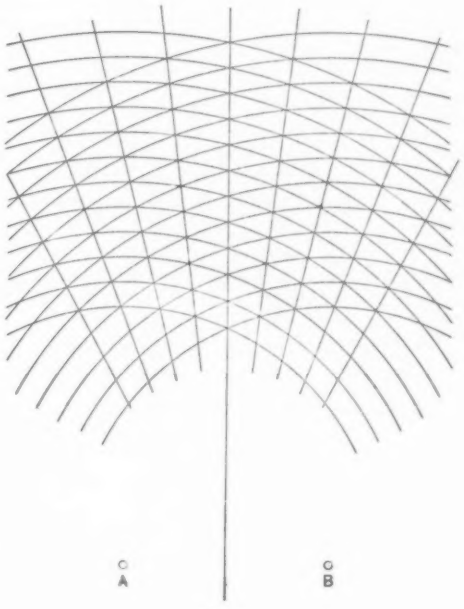


Fig. 1.

Consider next a thin film of air enclosed between two glass plates, with the light from a sodium burner falling upon the film at any angle, and being reflected from its two surfaces. The figures are plane sections perpendicular to the surfaces of the film, and passing through the source of light and the eye of the observer. The desired simplicity of treatment can only be attained by considering a somewhat ideal case, in which the effect due to refraction in the

upper glass plate is neglected. But the two portions of light which come by reflection from the two surfaces of the film are refracted by this plate in almost identical fashion, so that any relations which exist between them will not be appreciably changed thereby.

In Fig. 2, the two surfaces of the film are taken parallel. A is a particular point in the sodium flame which serves as the source of light, A' its image formed by reflection at the upper surface of the film, A'' that formed at the lower surface. The two reflected portions of light will then diverge from these two points as virtual sources. Finding the loci of the points of maximum disturbance as in Fig. 1, a_4 may represent the locus of points whose difference in distance from A' and A'' is four wavelengths, a_3 the similar locus for a difference in path of three wavelengths. In this and the following figures, the loci are constructed by locating two points on a chosen hyperbola, and drawing a straight line through them.

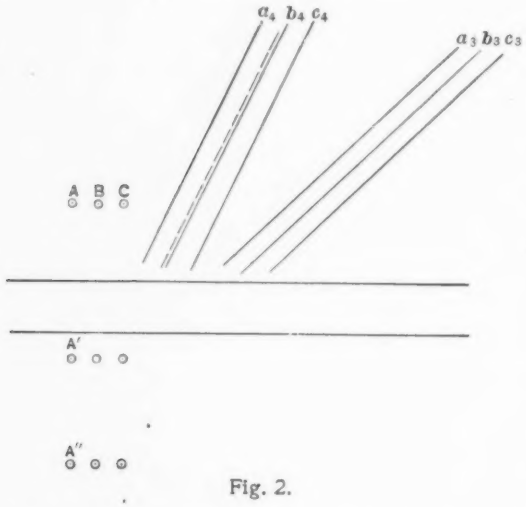


Fig. 2.

This construction is next carried out for two other points, B and C, on the luminous source, giving the loci b_4, c_4, and b_3, c_3. The three lines in each set are evidently parallel. There is actually a continuous series of luminous points across the source where it is intersected by the plane of the figure, and the loci for all of these points will similarly be parallel in each set. But for some point on the source, a locus of maximum disturbance will lie midway between a_4 and a_3, which will be the locus of minimum disturbance for the point A on the source. This overlapping of maxima and minima on a screen placed in the path of the reflected light will evidently prevent the formation of any definite interference effect. But if a

portion of this reflected light enter the eye, the observer will see a maximum illumination coming apparently along the path a_4 and all paths parallel to it, and therefore coming apparently from the point where these paths intersect, at infinity. Looking along a direction midway between a_4 and a_3, he will similarly see a minimum effect coming along a set of parallel paths. The interference fringes will then be clearly seen by the eye, or in a telescope, only when it is focused for parallel light.

It is of course to be noted that definite interference cannot occur between portions of light coming from two different points, A and B, on the source, but only between different portions of the light which originally came from a single point on the source.

There are other portions of the light from A which will emerge from the film after multiple reflection within it, and interference may occur among any two of these portions. The locus for one such case is shown by the dotted line in the figure; and it is evident that they will all be parallel to those already found.

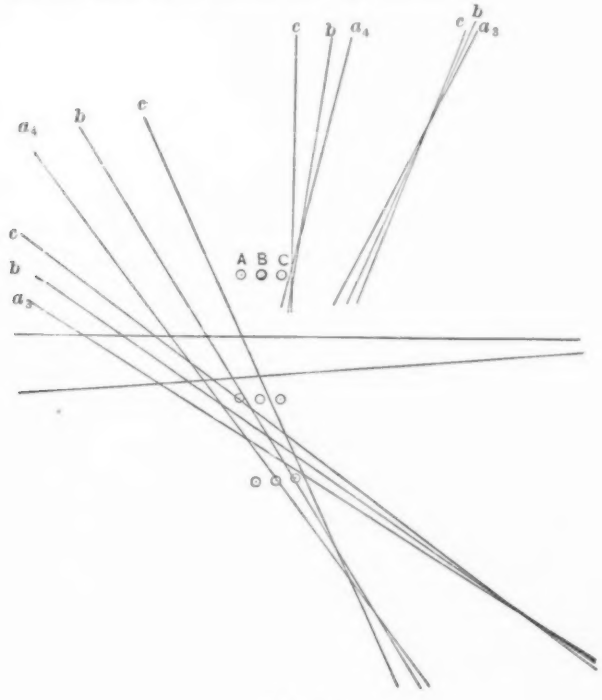


Fig. 3.

In Fig. 3 the same construction is applied to a wedge-shaped film. The two lines a_4 here represent two portions of the same hyperbola, in one case the light being reflected toward the angle of the wedge, in the other away from it. The two loci a and b now intersect at various points near the film. This means physically that at such a point of intersection there is a maximum of intensity in the illumination due to the point A on the source, and also in that due to B. It means, also, that the eye will see a maximum illumination coming along the two directions a and b, which will consequently seem to be localized at their intersection, and so a sharply defined bright fringe will be seen in a telescope focused upon this point.

The construction shows that any three loci do not in general intersect in a point. It is quite suggestive of the similar construction for the wave-normals of light obliquely refracted at a plane surface.

The distance of the fringes from the film varies with the angle of incidence, becoming zero, and changing sign, with it. The distance also varies with the thickness of the film; for if the film, imagined extended beyond the vertex, be moved toward the left, keeping the angle of incidence fixed, the fringes will pass through the film as the vertex, where the thickness is zero, passes the point of incidence. It is also evident that the distance will vary inversely with the angle of the film, for the distance becomes infinite when the angle becomes zero.

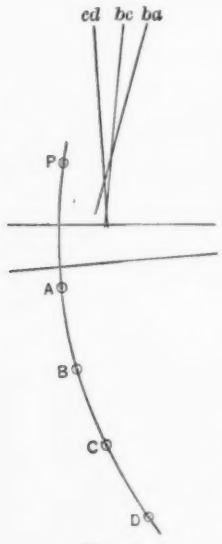


Fig. 4.

Fig. 4 shows the effect of multiple reflection within the film. A, B, C, D are four successive images of the single point P on the source. The three loci obtained by taking these images successively in pairs intersect in a way very similar to those in the corresponding position in Fig. 3.

If the film be composed of a refracting medium, as water, instead of air, the light reflected from the lower surface of the film will appear to come, not from a point, but from a caustic surface; or, for

a small pencil in any particular direction, from the circle of least confusion midway between two focal lines. Fig. 5 is an attempt to realize this condition graphically The caustic C represents the image of the point A on the source, formed by refraction at the upper surface of the film, and C' is its reflected image at the lower surface. For small angles of incidence, the effective image is quite near the cusp of the caustic, and the light which finally emerges from the film will them appear to come from points quite near the cusp of the caustic C''.

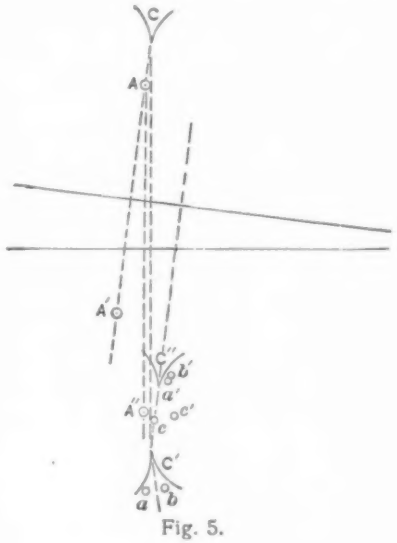


Fig. 5.

The substitution of water for air has thus moved the second image of A from A'' to the cusp of the caustic C'', which could also have been done by making the air film thinner, and of greater angle. Both of these changes would bring the fringes nearer to the film, for the same angle of incidence. The ratio of tangents of angles of film, multiplied by the ratio of thickness, deduced from the figure, is approximately one half. For small angles of incidence then the fringes should be about half as far from a water-film as from an air-film under similar conditions.

For a large angle of incidence, a and b may represent the effective images of A after reflection at the lower surface, for equal positive and negative values of the angle. For these two cases the cusp of the caustic C'' would be placed at c and c' respectively, and the final effective images of A, for light emerging from the upper surface, would be a' and b'. By the same reasoning that was used in the last paragraph, this shows that with increasing angle of incidence the distance of the water-fringes from the film does not increase so fast as that of the air-fringes. Also that the distance does not increase quite so fast for negative as for positive angles of incidence, negative angles being those for which the light is reflected away

from the angle of the film. The drawing is hardly exact enough to show this last point with certainty, although the others are quite clear.

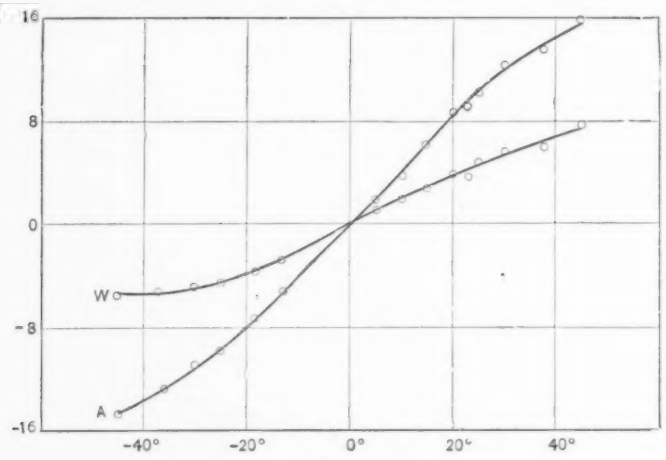


Fig. 6.

All of these conclusions were verified by a series of observations on a film enclosed between glass plates about 4 cm. long, in contact at one end and separated by two layers of tin-foil at the other. Small drops of water distributed irregularly in the film made it possible to observe the fringes in air and water, on either side of a boundary line, by merely changing the focus of the observing microscope without moving it laterally. The observations are plotted in Fig. 6, the curve *A* representing the results for the air-fringes and *W* for the water-fringes. Ordinates are distances in millimeters measured along the line of sight from film to fringes, and abscissæ are corresponding angles of incidence. It will be noted that for angles of incidence less than 20° the ratio of ordinates to the two curves is very nearly one half.

For angles of incidence greater than 45° the aberration becomes so great that measurements cannot be made with any accuracy.

It may be well to add that, for the sake of avoiding confusion, the phase difference of a half period introduced by the reflection within the glass, at the upper surface of the film, has been disregarded throughout.

UNIVERSITY OF CALIFORNIA,
BERKELEY, June, 1902.

ATTRACTIVE FORCE AND MAGNETIC INDUCTION.

By Geo. E. Poucher.

IT has been shown that for a magnet and its keeper the following formula holds :[1]

$$A = \frac{SB^2}{8\pi}$$

where A is the attractive force in dynes, B the magnetic induction, and S the area of the end of the bar in square centimeters. The experiment described in this paper is an attempt to test this law for objects not in immediate contact with the magnet.

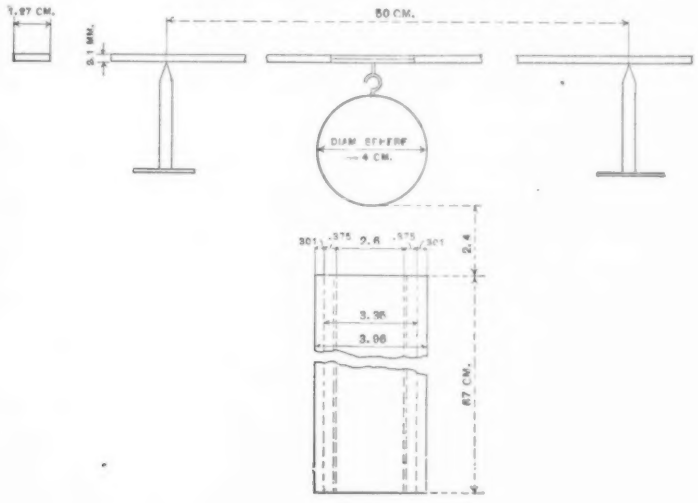


Fig. 1.

Following the method of Ewing (Magnetic Induction in Iron and Other Metals) B was determined from the formulæ $B = 4\pi I + H$ and

$$I = \frac{\overline{OQ}^2 F_1 \tan\theta}{\pi a^2 \left\{ 1 - \left(\frac{OQ}{OQ'} \right)^3 \right\}}.$$

[1] Kapp, Dynamos, Alternators, and Transformers, pp. 51–68.

Where OQ and OQ' are distances from the magnetometer needle to the ends of the magnet; a is the axis of the core of the magnet; F_1 is the value of H at the point considered. In this case $F_1 = 0.138$. Since H may be neglected in comparison with I we have

$$A = \frac{S}{8\pi}\left[\frac{4\pi\overline{OQ}^2 F_1 \tan\theta}{\pi a^2\left\{1 - \left(\frac{OQ}{OQ'}\right)^3\right\}}\right]^2.$$

All other terms being constants we wish to discover if $A \propto \tan^2\theta$.

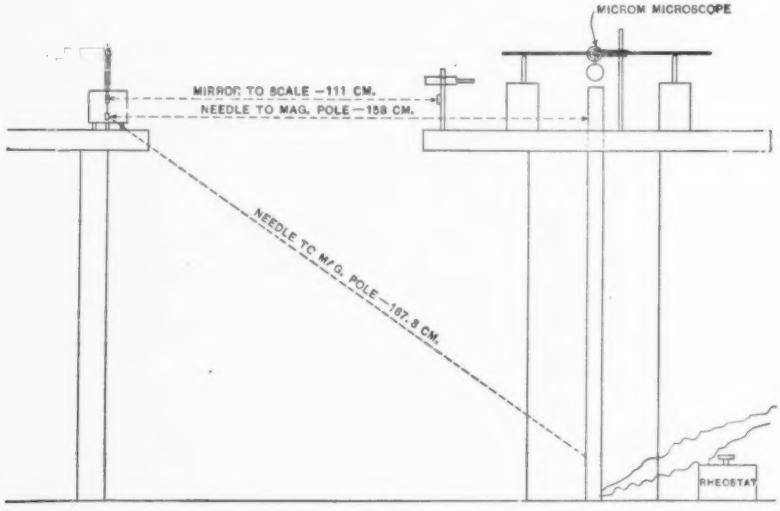


Fig. 2.

The apparatus, as seen in the Figs. 1 and 2, consisted of an electromagnet which had for a core a cylindrical soft-iron bar 2.6 × 67.0 cm. surrounded by a brass tube around which was wound the solenoid of two layers of wire, each of 6.5 turns to the centimeter. Above this was supported a copper bar 50.0 × 1.27 × 0.21 cm., from which was suspended a soft-iron sphere 4 cm. in diameter, directly over the magnet. The deflections of this bar were measured by a micrometer microscope focused on a black silk fiber stretched over the center of one side. A magnetometer was placed 158 cm. and afterwards at 135 cm. from the magnet, and its deflections were read by use of a telescope and scale.

The experiment consisted simply in reading the deflection of the magnetometer needle, and the approach of the sphere to the magnet when a current was sent through the coils. The tables and plots are self-explanatory. In making the latter allowance was made for the fact that as the sphere approached the magnet the attraction increased according to the law of inverse squares. This was necessarily rough as the magnet's action was complex.

TABLE I.

Amperes.	Magnetometer Scale Reading.	Tan² θ	Micr. Reading.
.71	4.6	.000289	.32
.98	6.5	.000576	.64
1.27	8.7	.001037	1.01
1.62	11.4	.001781	1.51
1.96	14.0	.002694	2.11
2.41	17.3	.004121	3.21
2.65	19.1	.005027	4.01
3.05	21.6	.006432	5.16
3.30	23.6	.007691	6.07
3.61	25.3	.009044	7.16
4.01	26.8	.009960	8.09
4.48	28.3	.011025	9.13
5.13	30.1	.012544	10.49

TABLE II.

Amperes.	Magnetometer Scale Reading.	Tan² θ	Micr. Reading.
.75	5.7	.000445	.21
1.02	7.8	.000835	.50
1.42	11.3	.001756	.95
1.99	16.3	.003721	1.95
2.34	18.5	.004720	2.81
2.84	22.3	.006872	4.23
3.05	23.7	.007762	5.05
3.61	27.1	.010201	6.87
3.98	28.9	.011664	7.85
4.43	30.8	.013225	9.06
5.08	32.9	.015129	10.26

At the conclusion of each reading the micrometer was tested for the zero point, and it was found that errors due to residual magnetism or the instability of the apparatus were negligible.

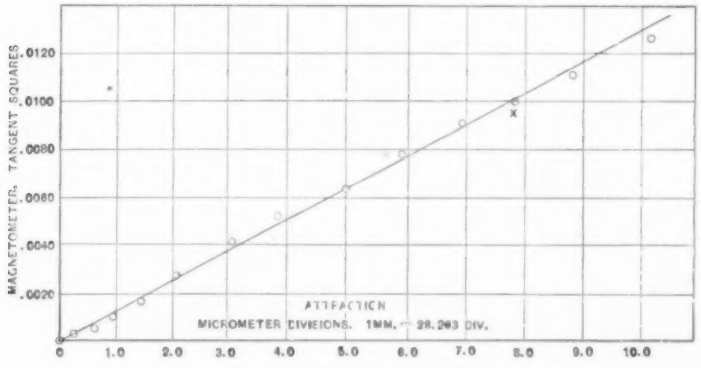


Fig. 3.

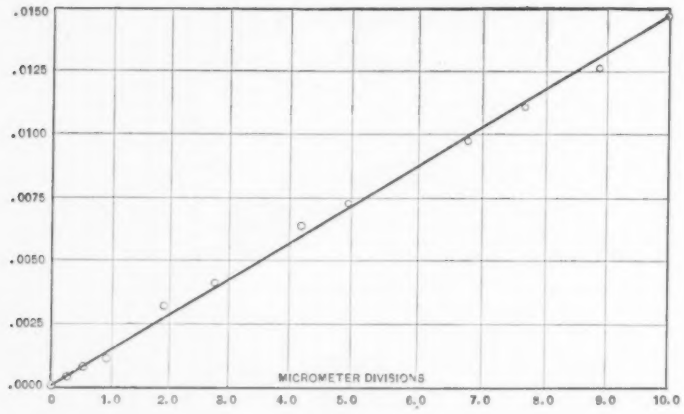


Fig. 4.

The exact relation between the induction and the attractive force expressed in Kapp's formula does not hold for objects at a distance from the magnet; but so far as these observations go they bear a constant relation to each other.

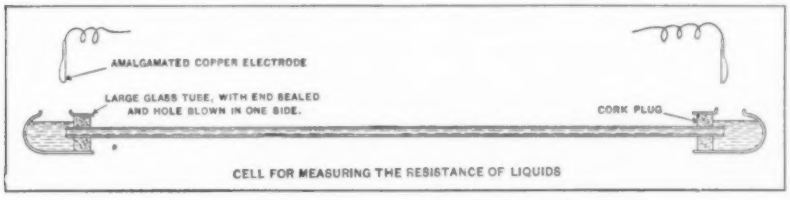
THE PHYSICAL LABORATORY,
UNIVERSITY OF MAINE.

A CELL FOR MEASURING THE ELECTRICAL RESISTANCE OF LIQUIDS.

By W. Walter Dinwiddie.

ALL instruments for a student laboratory should be so devised that the student can go to the bottom of what he is investigating without having to take anything on faith. In the usual forms of cells for measuring the resistance of liquids (Stewart and Gee, Elementary Practical Physics, Vol. 2, page 219), the student will either have to take the constant of the cell as given by the instrument maker, or use it first to measure the resistance of some liquid of which the resistance is assumed.

A very simple cell for determining the resistance of an electrolyte by Kohlrausch's method, which is free from this objection, may be constructed as follows:



CELL FOR MEASURING THE RESISTANCE OF LIQUIDS

Select a glass tube of uniform bore; cut it off a little more than a meter in length, then grind the end off until it is exactly one meter. Short pieces of tube of a much greater diameter, with the ends sealed and a large hole blown out on the side, are fitted on the ends with corks. The corks should be coated on the inside with shellac, or some substance not acted on by the liquid used.

The electrodes are made of copper, with one side ground smooth and amalgamated.

The tube is weighed with two small discs of glass to cover the ends, it is then filled with water and again weighed. Mercury may be used in place of water with some advantage, as it may be poured out and weighed alone.

One of the cells which the writer has constructed was found to contain 49.83 grammes of water at 26° C., at which the density of water is .9969, which gives .49902 sq. cm. for the mean cross-section. If the cross-section varies considerably a correction may be applied (Kohlrausch Physical Measurements, page 304), but the ones I have used were very nearly uniform.

In using the instrument the electrodes are first placed together and the resistance measured, then they are placed at the ends of the tube and the resistance measured again. The difference is the resistance of the liquid in the tube.

WASHINGTON, D. C.,
June 14, 1902.

ALFRED CORNU.

By George K. Burgess.

BY the death of M. Alfred Cornu, taken from his work in the prime of an active life, France has lost the senior member in physics of the Academy of Sciences and a well beloved teacher in the École Polytechnique, and the scientific world has lost with France a most able investigator and authority on physics, the successor of Fresnel and Fizeau.

Cornu began his work early in life in his chosen field of optics, his earliest work being on the mathematical theory of light, executed in the sixties and presented in a memoir to the Academy. In 1867 at the age of twenty-six he was appointed to the professorship in physics at the École Polytechnique, where he had been a student, a post that he filled with great distinction until his death last April.

In the early seventies he was engaged in the prosecution of three lines of experimental work all requiring the greatest skill,—the measurement of the velocity of light, the determination of the mean density of the earth, and a study of musical intervals. The year 1878 witnessed the brilliant completion of some six investigations of great value and their author was rewarded by the La Cage prize that year for the best work in physics and also by election to the Academy of Sciences to the chair of the second Becquerel.

Although Cornu devoted his energies to a considerable variety of questions in electricity, meteorology, astronomy and acoustics his work in optics is most prominent. He improved many optical instruments and methods and all his work is characterized by a directness, simplicity, and ready adaptation to the end in view; witness his photometer, his work in diffraction by the graphical representation of Fresnel's integrals by "Cornu's spirals," and his recent improvements of certain astronomical instruments. Among

the subjects that he shed light upon are the theory of reflection, diffraction, spectroscopy, double refraction, polarization, interference photometry, halos, photography, the relation of velocity to resistance in a medium, electrical machines, clocks, magnetism, and astronomy. Since 1885 there is not a volume of the *Comptes Rendus* that does not contain a valuable article from his pen. He was the first contributor to the *Journal de Physique* upon its foundation in 1872, and much of his work is naturally published there.

In 1879 he was a member of the French Transit of Venus Commission, and in 1886 he was made a member of the Bureau des Longitudes, the most distinguished scientific position in the gift of the French government. The Academy honored him by electing him its president in 1896—the year that Fizeau died—and his noble ideal is perhaps best given in the words of his inaugural address on that occasion:

"Utilitarianism is indeed one of the illnesses of our modern society, perhaps one of the gravest, because it tends to clip the wings of human flight towards the ideal and to lower it to the exclusive worship of material interests. The history of the great discoveries of the century, fruit of long, disinterested study, should on the contrary show that the sum of real progress is less in the exploiting of results acquired than in free, abstract, even fantastic investigations, in a word, in pure, independent science, wide open to all aspirations of the intellect."

A man who before large classes of young men was a teacher of great persuasion, with an unrivalled power of simplicity of presentation and clearness of exposition and a seldom equalled skill in demonstration, he was engaged in imparting to the youth of his country the common stock of physical knowledge and inspiring them with a love of scientific truth. As a member of the Bureau des Longitudes, engaged as an organizer of scientific facts and a leader in scientific discovery—this position above all marks him as one of the great authorities in physical science in his country. As a member of the Institute he was in the front rank of the great progressive movement of modern science as is shown by the rare value of his publications in the *Comptes Rendus* of that body—and it is hardly necessary to say that beyond the limits of France

he was also recognized as one of the eminent modern physicists, who, understanding and appreciating the traditions of scientific development in France as represented by the Institute, was yet in the front of the many-sided modern expansion of scentific influence.

As president of the French Physical Society he was recognized by younger men as their leader, and as a presiding officer he manifested those inborn qualities of tact, congenial appreciation, sympathetic attention and promptness, combined with an unusual felicity of speech—qualities that endear a president to his colleagues.

I have seen him, presiding at a meeting of the Physical Society, listen attentively, turned considerably with seemingly unflagged interest, while some less gifted physicist spent some two hours laboriously covering the details of an investigation, and then with a few well-chosen words of summing up and discriminating appreciation, said with such freshness and to the point, that the two hours were forgotten, or better, pleasantly remembered.

In the best sense of the word Cornu was a popularizer of science, particularly of applied science, as a glance over his contributions to the Annuaire du Bureau des Longitudes will show. He had the faculty of expressing most simply and directly yet thoroughly the results of any intricate scientific inquiry.

Pure science alone was not the limit of his field of activity and usefulness. As many other eminent French savants, Cornu was intensely interested in the welfare and good name of French industries. He wrote the introduction to the catalogue of optical instruments and of instruments of precision at the last Paris Exposition, and in many other ways gave his energy to the development of the construction of instruments that in many respects have not been equalled in other countries. He, in accordance with that admirable French tradition which separates the commercial so sharply from the professional, although the inventor of many optical instruments, never took out a patent.

His great scientific and administrative abilities were recognized also in his appointment as director of the Nice Observatory, recently given to the University of Paris. He was too a valuable member of the International Committee of Weights and Measures.

The last eminent position held by M. Cornu that brought him before the world of physicists was as President of the International Physics Congress held at Paris in 1900. The unqualified success of that Congress is a tribute to his genius as an organizer and as an inspirer of confidence. His charming personality, graciousness of address, cordiality of reception, frankness of manner and seriousness of purpose marked him as of that rare combination of the eminent man of science, the skilful executive and polished gentleman.

He was much sought after these last years to deliver public addresses, and the temper of the man is well shown in the close of his eulogy on Arago, which may be applied to himself:

"I cease, gentlemen, moved by the desire to recall some of the greatest of Arago's qualities. I perceive that many pages would be necessary to finish the sketch, however crude, of such a fruitful career. This task, besides, was not for me to perform; it has already been done on other solemn occasions by our masters, with an eloquence of which we have guarded a living memory; I should even have made excuse for speaking after them, if it were allowed to remain silent when we have to render homage to one of the noblest servants of science, of his country, of humanity."

UNIVERSITY OF CALIFORNIA,
May, 1902.

REFERENCES TO PAPERS ON LOW TEMPERATURE RESEARCH.

By J. S. Shearer.

THE rapid extension of facilities for research at low temperatures following the development of simple means for the liquefaction of gases makes a summary of papers dealing with recent work in this field quite convenient.

The following list begins with 1890. Doubtless many articles have been overlooked, but it is hoped that the list is fairly complete. The only intentional omissions are of papers entirely controversial in nature which add but little to our knowledge. References to the earlier literature may be found in Hardin's "Liquefaction of Gases" and in the papers of Dewar and Olzewski.

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PHYSICAL LABORATORY OF CORNELL UNIVERSITY,
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NEW BOOKS.

The Principles of Inorganic Chemistry. By WILHELM OSTWALD; translated by ALEXANDER FINDLAY. Pp. xxviii + 785. London, Macmillan and Co., 1902.

This translation brings into excellent English form the well-known recent work of Ostwald on General Chemistry. It is of great interest to the physicist to note the treatment accorded to the Elements of Chemistry by one to whom that important newer department of the science which goes by the name of physical chemistry owes so much. The physicist expects to find the physics of *chemistry proper* more adequately treated than has usually been the case in such text-books; and in this expectation he is in nowise disappointed.

The introduction of what may be called *physics proper* into books on chemistry is, of course, no new thing. Nearly all of the earlier authors found it necessary to devote a considerable space to the elucidation of such of the facts and principles of their sister science as were deemed necessary to the chemist. Thus the first 160 pages of Wöhler's translation of Berzelius's celebrated text-book of chemistry were given up to a preliminary outline of the principles of physics and this illustrious example was followed by many other authors at the beginning of the nineteenth century.

With the development of physics teaching in the universities this practice was gradually abandoned; but it has been taken up again by Ostwald and extended greatly beyond the original limits. Ostwald, to be sure, does not devote a separate and distinct portion of his book to the treatment of physics but introduces the subject from time to time as it may be needed. He deals, for example, with the general conceptions of *time* and *space*, *mass*, *weight*, *work* and *the forms of energy* in his introductory chapters; restates and discusses *Boyle's Law* and the *Law of Gay-Lussac* and also the subject of *temperature* in his chapter on oxygen; and so on to the end of the volume. The extent to which the physics of water is dealt with in the chapter devoted to that compound may be indicated briefly by noting that the topics in this chapter include *density*, *the coefficient of expansion*, *the degrees of freedom of liquid water*, *the properties of ice*, *super-cooling*, *heat of fusion and solidification*, *boiling*, *the hea of vaporization*, *super-heating*, *the influence of pressure on the melting point*

of ice, and the relations between the changes of the vapor pressure and of the freezing point. In pursuance of this plan of introducing appropriate physical conceptions from time to time throughout the book we find the critical phenomena of vapors discussed in the paragraphs dealing with the compounds of carbon; voltaic cells and their electromotive forces on the chapter on copper; storage batteries in the chapter on lead; and the Clark cell in that on mercury, etc.

Ostwald has not the justification of the earlier writers for this intermingling of the two sciences. Physics, like chemistry, is now taught everywhere. Are we to infer that he has been led to the introduction of so much that is universally familiar in elementary physics into his work because even in Germany he finds that students of chemistry are not acquainted with these matters, or is it a recognition that the two sciences are in reality one and inseparable and that there is no reason for attempting to distinguish between them? Surely there is nothing save the limitations of space and time to dictate the exclusion, as extraneous, from a text-book on the elements of chemistry, of elementary physics. There is no better time for the study of physics than when one is learning chemistry and *vice versa*.

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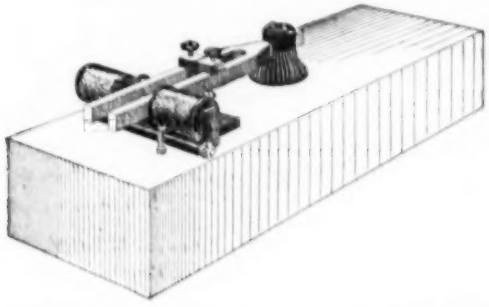

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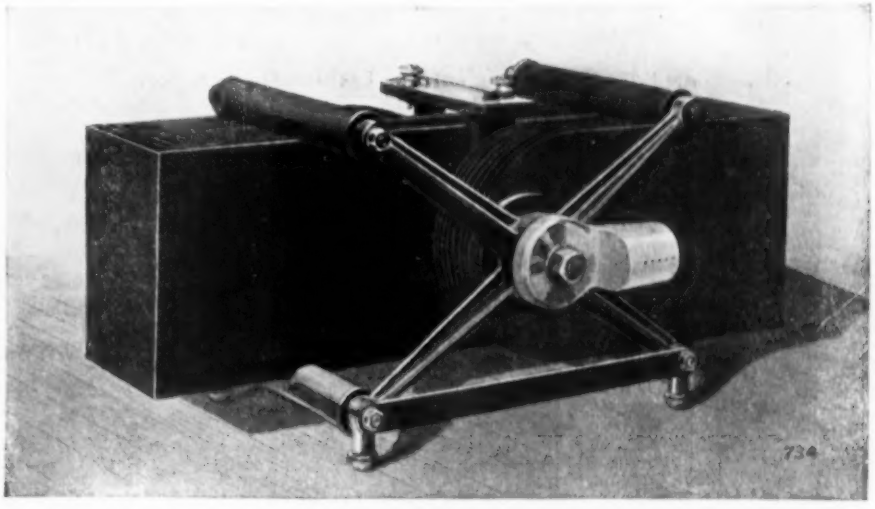

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